

# REPORT DOCUMENTATION PAGE

*Form Approved*  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

<b>1. REPORT DATE (DD-MM-YYYY)</b> 15-01-2007		<b>2. REPORT TYPE</b> Final		<b>3. DATES COVERED (From - To)</b> From 1-Feb-2004 to 31-Dec-2006	
<b>4. TITLE AND SUBTITLE</b> Quenching Dynamics of Electronically Excited Hydroxyl Radicals				<b>5a. CONTRACT NUMBER</b> FA9550-04-1-0068	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b>  Marsha I. Lester				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>  Department of Chemistry University of Pennsylvania Philadelphia, PA 19104-6323				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Dr. Michael R. Berman AFOSR/NL 875 N. Randolph St. Suite 325, Rm 3112 Arlington, VA 22203				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> AFOSR	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION / AVAILABILITY STATEMENT</b>  Unlimited <span style="float: right;">AFRL-SR-AR-TR-07-0019</span>					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> Collisional quenching of electronically excited OH $A^2\Sigma^+$ radicals by molecular partners has been investigated over the past 25 years, principally by evaluating the quenching cross sections for partners of aeronautical, atmospheric, and/or combustion relevance. Yet little is known about the outcome of these electronic quenching events, except that they facilitate the efficient removal of OH from the excited $A^2\Sigma^+$ electronic state by introducing nonradiative decay pathways. Most recently, we carried out the first experimental investigation of the nonreactive decay channel with molecular hydrogen by examining the quantum state distribution of the ground state OH $X^2\Pi$ products. The OH $X^2\Pi$ product state distribution is highly nonstatistical, with a strongly inverted rotational distribution for $v''=1$ , demonstrating that a significant torque is applied to OH as purely electronic energy is converted into internal excitation of the OH $X^2\Pi$ products. The high degree of rotational excitation is a direct manifestation of the forces in the vicinity of the conical intersection region(s) that lead to quenching.					
<b>15. SUBJECT TERMS</b> Hydroxyl radicals, quenching, nonadiabatic dynamics					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>  UU	<b>18. NUMBER OF PAGES</b>  7	<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b> U	<b>b. ABSTRACT</b> U	<b>c. THIS PAGE</b> U			<b>19b. TELEPHONE NUMBER (include area code)</b>

# AFOSR Final Report

FA9550-04-1-0068

## Quenching Dynamics of Electronically Excited Hydroxyl Radicals

Marsha I. Lester

Department of Chemistry, University of Pennsylvania  
Philadelphia, PA 19104-6323

19 January, 2007

### Objectives

A series of laboratory experiments has been conducted to examine the quenching dynamics of electronically excited hydroxyl radicals via collision-induced processes. The goal of these experiments was to elucidate the mechanism for nonadiabatic processes that transform electronically excited  $\text{OH } A \ ^2\Sigma^+$  radicals into ground state  $\text{OH } X \ ^2\Pi$  or reaction products. The research program encompassed studies of (1) quenching of  $\text{OH } A \ ^2\Sigma^+$  ( $v'=0$ ) by thermospheric gases through reactive and nonreactive pathways, (2) reactive quenching of  $\text{OH } A \ ^2\Sigma^+$  ( $v'=0$ ) by ground state hydroxyl radicals, and (3) reactive quenching of  $\text{OH } A \ ^2\Sigma^+$  ( $v'=0$ ) by methyl radicals. The kinetic energy profile and/or quantum state distribution of the  $\text{H } (^2\text{S})$ ,  $\text{O } (^3\text{P}_j)$ , and  $\text{OH } X \ ^2\Pi$  products will be ascertained from spectroscopic measurements and interpreted in the context of complementary first principles theoretical calculations. The research is addressing the role of nonadiabatic interactions in fundamental chemical processes, revealing the dynamical signatures associated with curve crossings and conical intersections between two or more potential energy surfaces. This study is of direct AFOSR relevance as the *reverse* chemical reactions,  $\text{O } (^3\text{P}) + \text{H}_2\text{O} \rightarrow \text{OH } A \ ^2\Sigma^+ + \text{OH}$  and  $\text{O } (^3\text{P}) + \text{CH}_4 \rightarrow \text{OH } A \ ^2\Sigma^+ + \text{CH}_3$ , are possible sources of the  $\text{OH } A \rightarrow X$  emission from the Space Shuttle's thruster plume. These laboratory measurements are needed to understand the chemical excitation pathways that lead to electronically excited  $\text{OH } A \ ^2\Sigma^+$  radicals in the interaction of the spacecraft's exhaust plume with the atomic oxygen atmosphere at orbital altitudes.

### Accomplishments

This section summarizes our accomplishments during the past three years of AFOSR

funding, 1-Feb-2004 through 31-Dec-2006. We have made significant progress on three different fronts. (1) New studies of the nonreactive outcome of OH  $A^2\Sigma^+$  collisional quenching events; (2) Fluorescence dip infrared spectroscopy of OH radicals in predissociative levels of the  $A^2\Sigma^+$  state; and (3) Experimental and theoretical studies of OH photoionization via the  $D^2\Sigma^-$  and  $3^2\Sigma^-$  Rydberg states. The next section summarizes our accomplishments in these areas.

Collisional quenching of electronically excited OH  $A^2\Sigma^+$  radicals by molecular partners has been extensively investigated over the past 25 years, principally by evaluating the quenching cross sections for partners of atmospheric and/or combustion relevance. Yet little is known about the outcome of these electronic quenching events, except that they facilitate the efficient removal of OH from the excited  $A^2\Sigma^+$  electronic state by introducing nonradiative decay pathways. For molecular hydrogen, Walch<sup>1</sup> and Yarkony<sup>2</sup> predict that the nonadiabatic pathways involve passage through conical intersection regions, which lead to ground state OH  $X^2\Pi$  radicals (nonreactive quenching) or reaction products. Previously, we made the first measurements of the reactive quenching process by characterizing the Doppler profiles of the H/D-atom products from collisions of electronically excited OH  $A^2\Sigma^+$  ( $v'=0$ ) with H<sub>2</sub>/D<sub>2</sub>.<sup>3</sup>

In this grant period, we carried out the first experimental investigation of the nonreactive decay channel by examining the quantum state distribution of the ground state OH  $X^2\Pi$  products.<sup>4</sup> In this work, a UV laser prepares the OH  $A^2\Sigma^+$  ( $v'=0, N'=0$ ) level in the collisional region of a pulsed supersonic expansion. After a short delay, a second UV laser probes the OH  $X^2\Pi$  ( $v'', J''$ ) produced from collisional quenching by exciting various rovibrational lines of the OH  $A-X$  transition, and collecting the induced fluorescence. The product state distribution of OH  $X^2\Pi$  is highly nonstatistical, with a strongly inverted rotational distribution for  $v''=1$ , demonstrating that a significant torque is applied to OH as 4.0 eV of purely electronic energy is converted into internal excitation of the OH  $X^2\Pi$  ( $v'', J''$ ) products. The high degree of rotational excitation appears to be a direct manifestation of the forces in the vicinity of the conical intersection region(s) that lead to quenching.<sup>2</sup> Thus, the highly nonstatistical OH  $X^2\Pi$  product state distribution observed following quenching of OH  $A^2\Sigma^+$  by molecular hydrogen provides valuable new information on the dynamical pathway through the conical intersection region(s) in the HO-H<sub>2</sub> system.

More recently, we reported a combined experimental and theoretical investigation of the

inelastic scattering channel resulting from electronic quenching of OH  $A^2\Sigma^+$  by molecular hydrogen.<sup>5</sup> The experiments utilize a pump-probe scheme to determine the OH  $X^2\Pi$  population distribution following collisional quenching in a pulsed supersonic expansion. The pump laser excites OH  $A^2\Sigma^+$  ( $v'=0, N'=0$ ), which has a significantly reduced fluorescence lifetime due to quenching by H<sub>2</sub>. The probe laser monitors the OH  $X^2\Pi$  ( $v'', N''$ ) population via laser-induced fluorescence on various  $A-X$  transitions under *single-collision* conditions. The experiments reveal a high degree of rotational excitation ( $N''$ ) of the quenched OH  $X^2\Pi$  products observed in  $v''=1$  and 2 as well as a pronounced propensity for quenching into the  $\Pi(A')$   $\Lambda$ -doublet level. These experiments have been supplemented by extensive multi-reference, configuration-interaction calculations aimed at exploring the topology of the relevant potential energy surfaces. Electronic quenching of OH  $A^2\Sigma^+$  by H<sub>2</sub> proceeds through conical intersections between two potentials of  $A'$  reflection symmetry (in planar geometry) that correlate with the electronically excited  $A^2\Sigma^+$  and ground  $X^2\Pi$  states of OH. The conical intersections occur in high-symmetry geometries, in which the O-side of OH points toward H<sub>2</sub>. Corroborating earlier work of Hoffman and Yarkony,<sup>2</sup> these calculations reveal a steep gradient away from the OH–H<sub>2</sub> conical intersection as a function of both the OH orientation and interfragment distance. The former will give rise to a high degree of OH rotational excitation, as observed for the quenched OH  $X^2\Pi$  products. An additional potential energy surface of  $A''$  reflection symmetry, correlating with OH  $X^2\Pi + H_2$ , does not have this pronounced angular gradient and, as a result, coplanar passage through the conical intersection would favor the observed  $\Pi(A')$   $\Lambda$ -doublet propensity.

Fluorescence-dip infrared (FDIR) spectroscopy, a UV-IR double resonance technique, has been employed to characterize the line positions, linewidths, and corresponding lifetimes of highly predissociative rovibrational levels of the excited  $A^2\Sigma^+$  electronic state of the OH radical.<sup>6</sup> Various lines of the  $4\leftarrow 2$  overtone transition in the excited  $A^2\Sigma^+$  state are observed, from which the rotational, centrifugal distortion, and spin-rotation constants for the  $A^2\Sigma^+$  ( $v=4$ ) state are determined, along with the vibrational frequency for the overtone transition. Homogeneous linewidths of 0.23 to 0.31 cm<sup>-1</sup> FWHM are extracted from the line profiles, demonstrating that the  $N=0-7$  rotational levels of the OH  $A^2\Sigma^+$  ( $v=4$ ) state undergo rapid predissociation with lifetimes of  $\leq 23$  ps. The experimental linewidths are in near quantitative agreement with first principle theoretical predictions by Parlant and Yarkony.<sup>7</sup>

A state-selected beam of hydroxyl radicals has been generated using a pulsed discharge source and hexapole field. The OH radicals are characterized by resonance enhanced multiphoton ionization (REMPI) spectroscopy via the nested  $D^2\Sigma^-$  and  $3^2\Sigma^-$  Rydberg states.<sup>8</sup> Simplified spectra are observed from the selected  $|M_j|=3/2$  component of the upper  $\Lambda$ -doublet level of the lowest rotational state ( $J=3/2$ ) in ground ( $v''=0$ ) and excited ( $v''=1-3$ ) vibrational levels of the OH  $X^2\Pi_{3/2}$  state. Two-photon transitions are observed to the  $D^2\Sigma^-$  ( $v'=0-3$ ) and  $3^2\Sigma^-$  ( $v'=0,1$ ) vibronic levels, extending previous studies to higher vibrational levels of the Rydberg states. Spectroscopic constants are derived for the Rydberg states and compared with prior experimental studies. Complementary first-principle theoretical studies of the properties of the  $D^2\Sigma^-$  and  $3^2\Sigma^-$  Rydberg states by van der Loo and Groenenboom<sup>9</sup> are used to interpret the experimental findings and examine the utility of (2+1) REMPI for sensitive detection of OH radicals.

## Equipment

N/A

## Personnel

This grant has partially supported the research of graduate students Margaret Greenslade, Erika Derro, Ilana Pollack, Logan Dempsey, and Eunice Li. In addition, postdoctoral researchers Patricia Cleary, Craig Murray, and Ian Konen worked part-time on this project.

## Interactions/Transitions

I have collaborated with Millard Alexander on the theoretical aspects of this project and had informal discussions with David Yarkony. In addition, my group collaborated with David Parker at Nijmegen (the Netherlands) on velocity map imaging studies of H ( $^2S$ ) and O ( $^3P$ ) products following photodissociation OH/D radicals at 243 and 226 nm, respectively, and REMPI studies of OH. Finally, I have worked with Rainer Dressler and colleagues at Hanscom AFB on the analysis of OH emission data from the Space Shuttle's thruster plume.

## Inventions and patent disclosures

There have been no inventions leading to patent disclosures during the period of this grant.

## References

1. M. I. Lester, R. A. Loomis, R. L. Schwartz, and S. P. Walch, *J. Phys. Chem. A* **101**, 9195 (1997).
2. D. R. Yarkony, *J. Chem. Phys.* **111**, 6661 (1999); B. C. Hoffman and D. R. Yarkony, *ibid.* **113**, 10091 (2000).
3. D. T. Anderson, M. W. Todd, and M. I. Lester, *J. Chem. Phys.* **110**, 11117 (1999); M. W. Todd, D. T. Anderson, and M. I. Lester, *J. Phys. Chem. A* **105**, 10031 (2001).
4. I. B. Pollack, Y. Lei, T. A. Stephenson, and M. I. Lester, *Chem. Phys. Lett.* **421**, 324 (2006).
5. P. A. Cleary, L. P. Dempsey, C. Murray, M. I. Lester, J. Kłos, and M. H. Alexander, *J. Chem. Phys.*, submitted for publication (2007).
6. E. L. Derro, I. B. Pollack, L. Dempsey, M. E. Greenslade, Y. Lei, D. Č. Radenović, and M. I. Lester, *J. Chem. Phys.* **122**, 244313 (2005).
7. G. Parlant and D. R. Yarkony, *J. Chem. Phys.* **110**, 363 (1999).
8. M. E. Greenslade, M. I. Lester, D. Č. Radenović, A. J. A. van Roij, and D. H. Parker, *J. Chem. Phys.* **123**, 074309 (2005).
9. M. P. J. van der Loo and G. C. Groenenboom, *J. Chem. Phys.* **123**, 074310 (2005).

## Publications acknowledging AFOSR support

- 1) M. E. Greenslade, M. I. Lester, D. Č. Radenović, A. J. A. van Roij, and D. H. Parker, “(2+1) Resonance Enhanced Ionization Spectroscopy of a State Selected Beam of OH Radicals”, *J. Chem. Phys.* **123**, 074309 (2005).
- 2) E. L. Derro, I. B. Pollack, L. Dempsey, M. E. Greenslade, Y. Lei, D. Č. Radenović, and M. I. Lester, “Fluorescence Dip Infrared Spectroscopy and Predissociation Dynamics of OH A  $^2\Sigma^+$  ( $v=4$ ) Radicals”, *J. Chem. Phys.* **122**, 244313 (2005).
- 3) I. B. Pollack, Y. Lei, T. A. Stephenson, and M. I. Lester, “Electronic Quenching of OH A  $^2\Sigma^+$  Radicals in Collisions with Molecular Hydrogen”, *Chem. Phys. Lett.* **421**, 324-328 (2006).

- 4) P. A. Cleary, L. P. Dempsey, C. Murray, M. I. Lester, J. Kłos, and M. H. Alexander, "Electronic Quenching of OH  $A^2\Sigma^+$  Radicals in Single Collision Events with Molecular Hydrogen: Quantum State Distribution of the OH  $X^2\Pi$  Products" J. Chem. Phys., submitted for publication (2007).